Comparisons and Combinations of Reactor and Long-Baseline Neutrino Oscillation Measurements

K. B. M. Mahn* and M. H. Shaevitz†

Department of Physics, Columbia University, New York, NY 10027

(Dated: February 4, 2008)

Abstract

We investigate how the data from various future neutrino oscillation experiments will constrain the physics parameters for a three active neutrino mixing model. The investigations properly account for the degeneracies and ambiguities associated with the phenomenology as well as estimates of experimental measurement errors. Combinations of various reactor measurements with the expected J-PARC (T2K) and NuMI offaxis (Nova) data, both with and without the increased flux associated with proton driver upgrades, are considered. The studies show how combinations of reactor and offaxis data can resolve degeneracies (e.g. the θ_{23} degeneracy) and give more precise information on the oscillation parameters. A primary purpose of this investigation is to establish the parameter space regions where CP violation can be discovered and where the mass hierarchy can be determined. We find that, even with augmented flux from proton drivers, such measurements demand that $\sin^2 2\theta_{13}$ be fairly large and in the range where it is measurable by reactor experiments.

PACS numbers: 14.60.Pq, 14.60.St, 12.15.Ff

*Electronic address: kendallm@phys.columbia.edu

†Electronic address: shaevitz@nevis.columbia.edu

The worldwide program to understand neutrino oscillations and determine the mixing parameters, CP violating effects, and mass hierarchy will require a broad combination of measurements. Progress in the past associated with solving the solar and atmospheric neutrino puzzles took a full suite of experiments to isolate and understand the phenomenology. Each additional measurement helped define the direction of future studies. One would expect a similar chain for the current goals where the program grows as information is obtained. This study attempts to see how various present proposals for next generation experiments (including two detector reactor and accelerator based long-baseline experiments) compare to and complement each other. A particular emphasis is on combining experiments to give improved physics parameter determination. As in the past, the best constraints on the phenomenology come from combining data from different processes and setups.

I. PROCEDURE FOR THIS STUDY

For a three active neutrino scenario, neutrino oscillations are described by six physics parameters: $\theta_{13}, \theta_{12}, \theta_{23}, \Delta m^2_{12}, \Delta m^2_{23}$, and the CP violation phase, δ. In addition, a full description requires knowing the hierarchy of mass state 3 relative to 1 and 2, *i.e.* the sign of Δm^2_{23}. (See Ref.[1, 2] for a description of three neutrino oscillation phenomenology and current results of global fits.)

The oscillation probability up to second order for reactor and long-baseline measurements is given by [1]

$$P_{reactor} \simeq \sin^2 2\theta_{13} \sin^2 \Delta + \alpha^2 \Delta^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}, \tag{1}$$

$$\begin{aligned} P_{long-baseline} \simeq & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\ & \mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\ & + \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin^2 \Delta \\ & + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta \end{aligned} \tag{2}$$

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$.

In the investigations shown here, the full formulae for the oscillation probability have been used as incorporated in a computer program developed by S. Parke [3]. The higher

order corrections for the reactor probability are quite small for the distances on the scale of the reactor experiments considered here, and so, approximately, a measurement of $P_{reactor}$ directly constrains the mixing parameter θ_{13}. On the other hand, the full expression for the long-baseline probability introduces many degeneracies and correlations between the physics parameters θ_{23} and δ_{CP}, plus the mass hierarchy through matter effects even before experimental uncertainties are taken into account [1, 4]. Therefore, a measurement of $P_{long-baseline}$ corresponds to sizable regions in the physics parameter space.

Of the six parameters, we assumed for this study that $\theta_{12}, \theta_{23}, \Delta m^2_{12}$, and Δm^2_{23} are known to the precision expected from either the current program (Super-K, Minos and CNGS) or the future program (Nova and T2K), as shown in Table I. This leaves for determination θ_{13}, δ, and the mass hierarchy, which are the subject of this study.

The technique we will use for this study is as follows. We generate data according to the experimental expectations with the underlying physics assumptions and assumed parameters. We then explore the parameter space for one of the measurement parameters in terms of $\Delta\chi^2$ values. For a given set of parameters, a χ^2 value is found by comparing the prediction with these parameters to the orginally generated data. The difference between this χ^2 value and the one calculated with the original parameters is the $\Delta\chi^2$ value. In each case, we will explore the change due to the variation of only one parameter. However, estimating a correct sensitivity depends on the choices of all six of the parameters described above. We handle these inherent ambiguities by choosing the most conservative (lowest) $\Delta\chi^2$ value for the parameter being tested by marginalizing over all the other parameters. For example, if we are studying θ_{13}, for each value of θ_{13} studied, the other parameters $\delta_{CP}, \Delta m^2_{23}$ (including sign) and θ_{23} are allowed to vary within the allowed ranges. This sometimes results in discontinuities, where one hierarchy becomes worse than the other in a certain region. The best choices are determined by minimizing the $\Delta\chi^2$ value using the Minuit[5] program.

The other experimental inputs for the study are given in Table II and are derived from estimates of the measurement sensitivities. For these sensitivities, we have taken the values from the given experiment's estimates without further study. Three types of two detector reactor experiments are considered corresponding to a small (Double-CHOOZ, [6]), medium (Braidwood [7], Daya Bay [8]), or large (MiniBooNE size) detector reactor $\overline{\nu}_e$ measurements. The sensitivities for the reactor experiments are scaled from the $\sin^2 2\theta_{13}$ 90% C.L. limits

Parameter	Value	Current Uncertainty (1σ)	Future Uncertainty ($1\ \sigma$)
$\sin^2 2\theta_{23}$	1.0	0.1 (Super-K)	0.01 (T2K)
$\Delta m^2_{23}(\mathrm{eV}^2)$	2.5×10^{-3}	0.55×10^{-3} (Super-K)	0.1×10^{-3} (T2K)
$\theta_{12}(\deg)$	32.31	2.55 (global solar fit)	–
$\Delta m^2_{12}(\mathrm{eV}^2)$	7.9×10^{-5}	0.55×10^{-5} (global solar fit)	–

TABLE I: Current and future uncertainty estimates on oscillation parameters from Super-Kamiokande [9], T2K [10], and a global solar fit by Kamland [11]. The studies here use the above values except the central value of $\sin^2 2\theta_{23}$ is assumed to be 0.95 (see text).

at $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 for a null oscillation scenario. In terms of integrated luminosity defined as detector mass [tons] $\times$ thermal reactor power [GW]$\times$ running time [years], the three options correspond to 300, 3000, and 20,000 ton·GW·yrs for the small, medium, and large reactor scenarios. The assumed 90% C.L. limits on $\sin^2 2\theta_{13}$ for the three scenarios are then given by 0.03, 0.01, and 0.005, for small, medium, and large detector reactor experiments, respectively.

Two offaxis long-baseline experiments are considered, J-PARC to Super-K[10] (T2K) and the NuMI offaxis proposal[12] (Nova). For these experiments, the uncertainties are scaled from the expected number of events given in the Nova Proposal for 10km offaxis [13] and a talk by Nakaya given at NOON 2003 [14]. The given uncertainties include statistical errors associated with the background and signal for a 5 year data run but do not include any systematic uncertainty. In the studies presented here, results are given for various data running periods with the nominal beam rates corresponding to Table II. In addition, some results are given for upgraded beams with five times the flux as would be appropriate for the T2K Phase II experiment or the Nova experiment with a new proton driver. We consider the different cases of running only with neutrinos, or with neutrino and antineutrino running with the number of years of neutrino and antineutrino running specified for each plot. The uncertainty on the θ_{23} parameter can have a significant effect on the long-baseline measurements since the quantity that is constrained as given in Table I is $\sin^2 2\theta_{23}$, and the parameter that modulates the long-baseline oscillation probability is $\sin^2 \theta_{23}$. This can lead to a 60% uncertainty in the oscillation probability for $\sin^2 2\theta_{23} = 0.95$.

For the studies presented in this report, the uncertainties due to the variations of θ_{23},

Experiment	Basis of Estimate	Osc. Prob. and σ for $\sin^2 2\theta_{13} =$		
		0.02	0.05	0.10
Reactor ($E_\nu = 3.6$ MeV)	$\sin^2 2\theta_{13}^{Limit}$			
Small 1.05 km	$0.03@90\%CL$	0.013 ± 0.012	0.033 ± 0.012	0.064 ± 0.012
Medium 1.8 km	$0.01@90\%CL$	0.022 ± 0.006	0.052 ± 0.006	0.102 ± 0.006
Large 1.8 km	$0.005@90\%CL$	0.022 ± 0.003	0.052 ± 0.003	0.102 ± 0.003
T2K ($E_\nu = 650$ MeV)	Number of events in 5 yrs:			
$\langle L \rangle = 295$ km				
ν	105.0 signal / 17.8 bkgnd	0.010 ± 0.003	0.023 ± 0.004	0.044 ± 0.006
$\overline{\nu}$	30.8 signal / 10.2 bkgnd	0.009 ± 0.007	0.020 ± 0.008	0.038 ± 0.010
Nova ($E_\nu = 2.1$ GeV)	Number of events in 5 yrs:			
$\langle L \rangle = 810$ km				
ν	227.4 signal / 39.0 bkgnd	0.010 ± 0.002	0.024 ± 0.003	0.045 ± 0.004
$\overline{\nu}$	109.0 signal / 18.5 bkgnd	0.008 ± 0.003	0.017 ± 0.005	0.032 ± 0.006

TABLE II: Estimates of the experimental uncertainties for future oscillation experiments. The last three columns indicate the oscillation probability and respective error for three different values of $\sin^2 2\theta_{13}$. For the long-baseline experiments, the number of events and sensitivity is given for 5 years of neutrino mode and 5 years of antineutrino mode separately. The given uncertainties include statistical errors associated with the background and signal for a 5 year data run, but do not include systematic uncertainty. $\Delta m^2_{23} = 2.5 \times 10^{-3}\text{eV}^2$ for all estimates and additionally, $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$ for the long baseline experiment's event rates.

Δm^2_{23}, and the mass hierarchy are included. In the $\overline{\nu}$ data, there is a 5% to 10% contamination of ν induced events in the sample. For the studies presented here, we use 5% for Nova, and 10% for T2K, as estimated by the experiment. To summarize, the following list gives the parameters used for the various fit results and the values and typical uncertainties for the parameters that are varied:

- Δm^2_{23} ($\approx \Delta m^2_{13}$) $= 2.5 \times 10^{-3}$ eV^2 and allowed to vary within its future expected uncertainty (typical $\sigma = 0.1 \times 10^{-3}$ eV^2). We include the hierarchy ambiguity associated with Δm^2_{23} being < 0 or > 0.

- $\sin^2 2\theta_{23} = 0.95$ and allowed to vary within its future expected uncertainty (typical $\sigma = 0.01$). We include the ambiguity associated with θ_{23} being $< 45°$ or $> 45°$.
- Δm^2_{12} held fixed at 7.9×10^{-5} eV^2.
- θ_{12} held fixed at $32.31°$.
- δ_{CP} allowed to vary between $0°$ to $360°$.
- $\sin^2 2\theta_{13}$ allowed to vary between 0.0 and 0.3.

II. 90% C.L. ALLOWED RANGE OF θ_{13}

The θ_{13} mixing angle is as yet undetermined in the current neutrino oscillation phenomenology. It is known to be smaller than the other mixing angles. The size of θ_{13} is an important ingredient in constraining models of neutrino masses and mixing, such as attempts to relate the quark and lepton mixings. The size of this mixing angle also has important implications for long-baseline ν_e appearance measurements because it scales the size of the oscillation probability.

As an indication of how well a given measurement can constrain the value of θ_{13}, Figure 1 (left: T2K, right: Nova) shows the 90% C.L. allowed regions associated with measurements of a null oscillation scenario where the true value of $\sin^2 2\theta_{13}$ is equal to zero. The grey region (white curve) is the 90% C.L. allowed region for the two long-baseline experiments for a three year neutrino only run with the nominal ($\times 5$) beam rate. Combining the long-baseline and medium reactor measurement gives the improved black region.

If θ_{13} is large enough, then positive signals will be observed by the experiments. Under these circumstances, the goal would be to make the best determination of the mixing parameter. Figure 2 shows the 90% C.L. regions that would be obtained for an underlying scenario where $\sin^2 2\theta_{13} = 0.05$. As shown, a long-baseline only measurement will not determine the mixing parameter θ_{13} very well with an allowed region that spans from 0.025 to over 0.11. On the other hand, a reactor experiment with at least the medium scale sensitivity measures $\sin^2 2\theta_{13}$ to about 10% or θ_{13} to $\pm 0.4°$.

As seen from the figures, the reactor measurements are very efficient at constraining the value of θ_{13}. Even a small reactor experiment can probe for an early indication if the

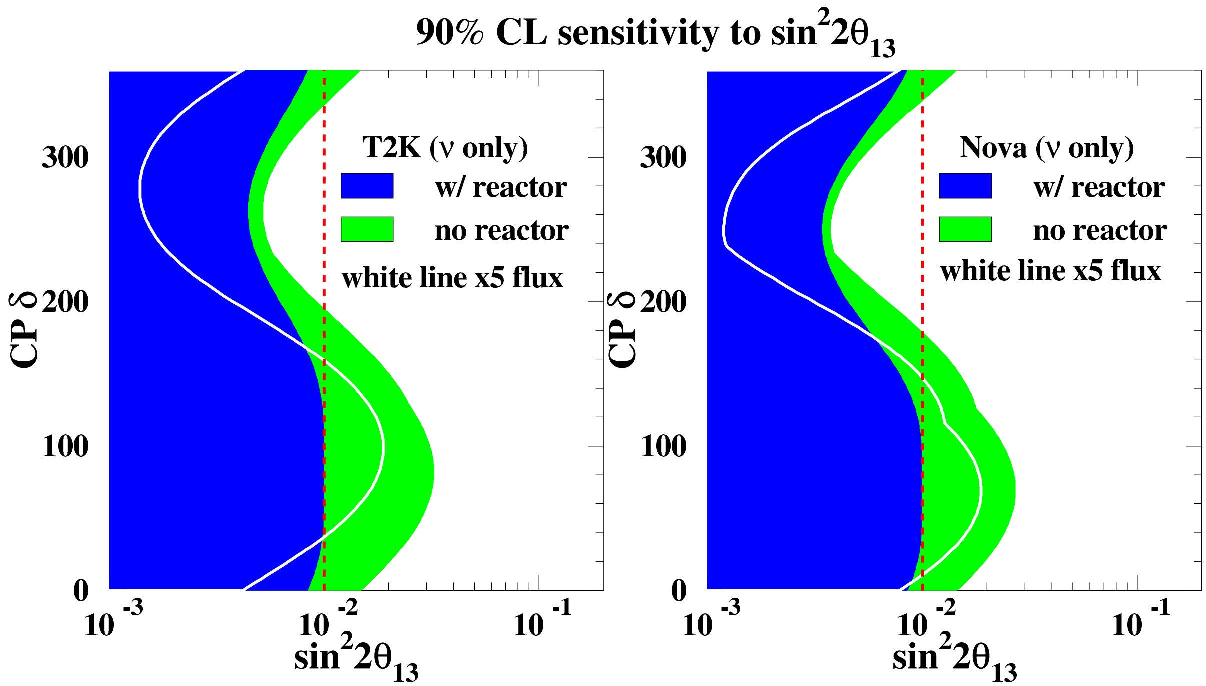

FIG. 1: 90% C.L. upper limit regions for various oscillation measurements for an underlying null oscillation scenario where $\sin^2 2\theta_{13} = 0$ ($\sin^2 2\theta_{23} = 0.95 \pm 0.01$, $\Delta m^2 = 2.5 \pm 0.1 \times 10^{-3}$ eV^2 and $\delta_{CP} = 0°$). The left (right) plot is for the T2K (Nova) long-baseline experiment. The grey region is the 90% C.L. allowed region for the long-baseline experiments for a three year neutrino only run with nominal beam rate. The white line is the limit of the 90% C.L. allowed region for a three year, neutrino only run at 5× the nominal beam rate. The black region gives the combination of three year long-baseline runs with a medium reactor measurement. The vertical dashed line indicates the 90% CL upper limit for a medium reactor experiment alone.

value is sizable. The large reactor experiment has sensitivity comparable to planned long-baseline experiments and the medium scale experiment can measure values in the range for $\sin^2 2\theta_{13} > 0.02$ at the 10% to 30% level. As will be seen in later plots, studies of CP violation and matter effects over the next decade are only possible if $\sin^2 2\theta_{13}$ is significantly larger than about 0.01. A small or medium scale reactor experiment can establish if these studies will be possible and, if they are, add additional information for determining the mixing parameters.

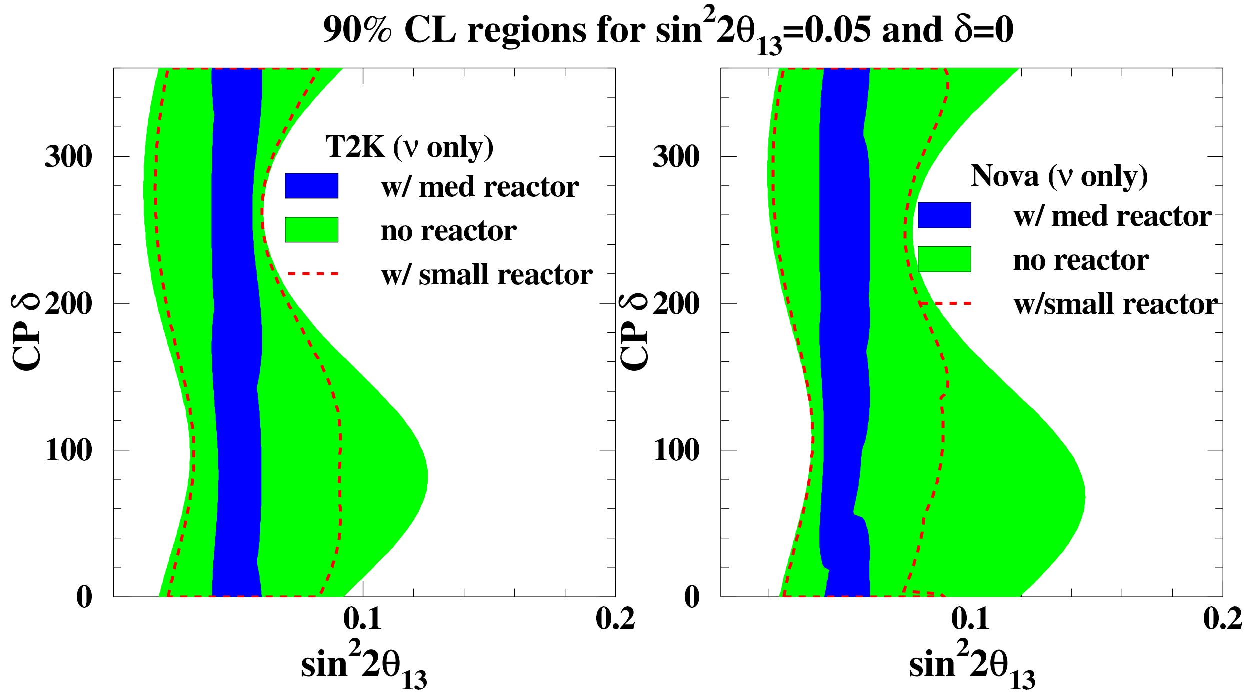

FIG. 2: 90% C.L. regions for underlying oscillation parameters of $\sin^2 2\theta_{13} = 0.05$, $\sin^2 2\theta_{23} = 0.95 \pm 0.01$, $\Delta m^2 = 2.5 \pm 0.1 \times 10^{-3}$ eV^2 and $\delta_{CP} = 0°$. The grey regions are for the T2K (left plot) or Nova (right plot) experiments for three years of neutrino running. The black regions are the 90% C.L. allowed regions for a combined medium reactor plus long-baseline analysis. The dashed lines indicate how the combined measurement would degrade with the small reactor sensitivity.

III. RESOLUTION OF THE θ_{23} DEGENERACY

The mixing angle θ_{23} is an important parameter in developing an understanding of the mixing matrix and for proceeding with a determination of θ_{13}. In many theoretical models, θ_{23} is not expected to be 45° and the difference from this value, both in sign and magnitude, may lead to a deeper understanding of the mixing.

Information on the value of θ_{23} has been obtained from ν_μ disappearance measurements in the atmospheric Δm^2 region, such as the Super-K and K2K experiments. These experiments restrict the allowed region of $\sin^2 2\theta_{23}$. Unfortunately, a single value of $\sin^2 2\theta_{23} = a$ corresponds to two possible solutions for θ_{23}, $\frac{1}{2}\sin^{-1}(\sqrt{a})$ or $\frac{\pi}{2} - \frac{1}{2}\sin^{-1}(\sqrt{a})$. The current Super-K measurement of $\sin^2 2\theta_{23} = 1.00 \pm 0.1$ corresponds to values of $\theta_{23} = 45° \pm 9.22°$. For the determination of θ_{13} using a long-baseline $\nu_\mu \to \nu_e$ appearance measurement, this

ambiguity presents a problem since the oscillation probability is proportional to $\sin^2\theta_{23}$, as shown in Equation 1. The present Super-K measurement would correspond to a change in the T2K or Nova oscillation probability of about 63%, for a change in θ_{23} from 35.78° to 54.22°.

This ambiguity in the determination of θ_{23} is difficult for a long-baseline $\nu_\mu \to \nu_e$ appearance measurement to resolve, but can be well addressed with a combination of reactor and long-baseline measurements (see Ref. [16, 17]). Figure 3 shows examples of different combinations of long-baseline results with (black regions) or without (grey regions) the inclusion of a medium scale reactor measurement. (The dashed curve is for the inclusion of a small, Double-CHOOZ type measurement.) For this analysis, $\sin^2 2\theta_{23} = 0.95 \pm 0.05$, $\sin^2 2\theta_{13} = 0.05$, and $\delta_{CP} = 270°$. As shown, the medium scale reactor data resolves this degeneracy to some degree when combined with antineutrino running, however a small (Double-CHOOZ) reactor experiment does not at all.

Future measurements of ν_μ disappearance in the atmospheric Δm^2 region by the T2K or Nova experiments could reduce the uncertainty in $\sin^2 2\theta_{23}$ to order 0.01 [10], but would still leave the θ_{23} vs. $\frac{\pi}{2} - \theta_{23}$ ambiguity. Figure 4 shows the different combinations of long-baseline results with or without the inclusion of a medium scale reactor measurement for $\sin^2 2\theta_{23} = 0.95 \pm 0.01$. Again, the medium scale reactor resolves the degeneracy when combined with T2K and Nova neutrino and antineutrino running, whereas the small reactor does not.

In general, the regions of the δ versus $\sin^2 2\theta_{13}$ plane where this degeneracy can be resolved at the two standard deviation level is shown in Fig. 5. From the figure, it is seen that resolving this ambiguity puts a premium on including reactor data with good precision. Combined with the upgraded off-axis data, a medium (large) scale reactor experiment can cover most of the parameter space for $\sin^2 2\theta_{13}$ values greater than 0.05 (0.025). If $\sin^2 2\theta_{23}$ turns out too much different from 1.0, resolving this ambiguity will become very important to making progress toward determining the CP phase and the mass hierarchy.

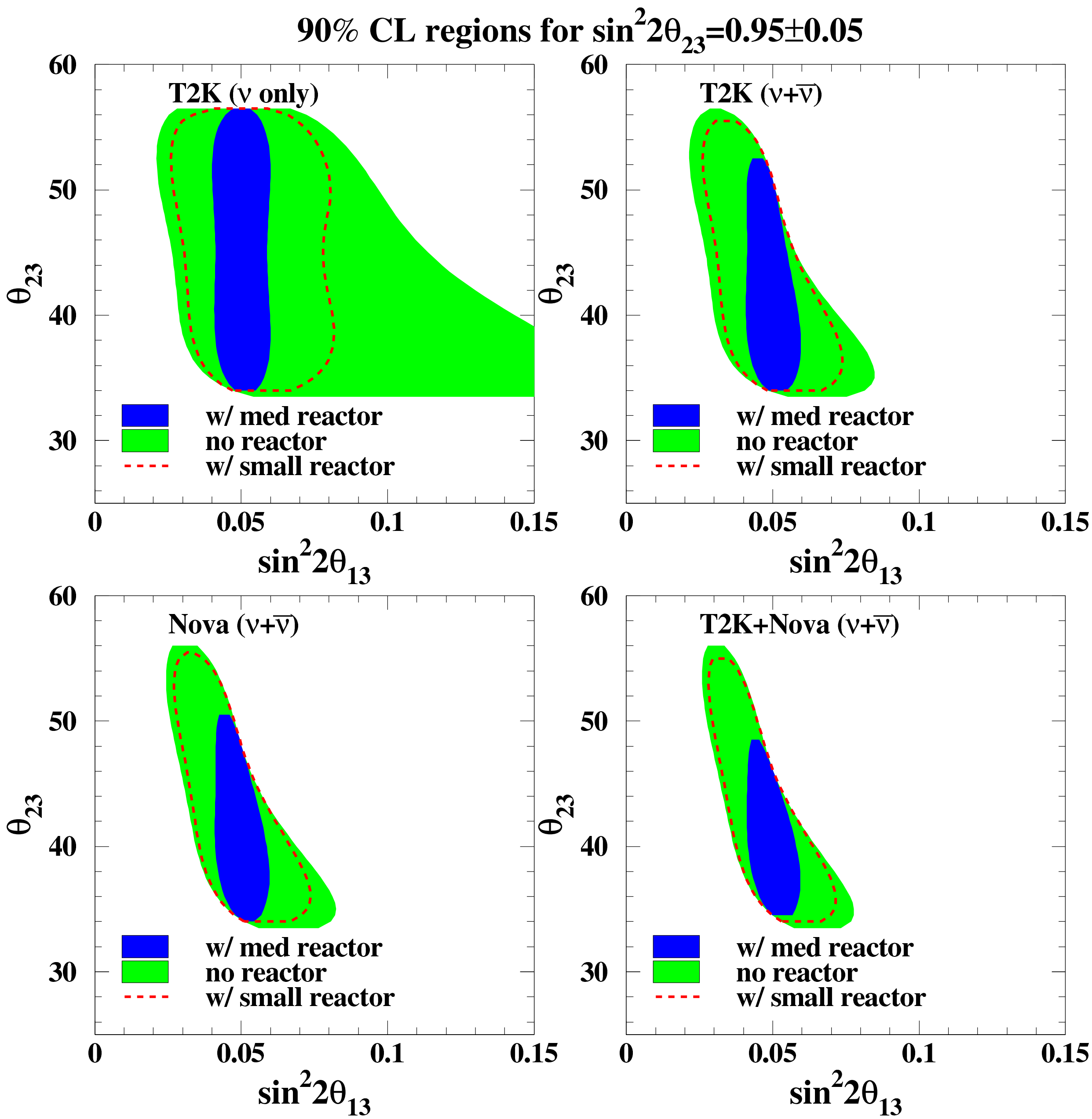

FIG. 3: 90% C.L. allowed regions for simulated data with underlying oscillation parameters of $\sin^2 2\theta_{13} = 0.05$, $\theta_{23} = 38.54°$, $\Delta m^2 = 2.5 \pm 0.1 \times 10^{-3}$ eV^2 and $\delta_{CP} = 270°$. The analysis includes the restriction that $\sin^2 2\theta_{23} = 0.95 \pm 0.05$. The grey regions are for various long-baseline combinations of the T2K and Nova experiments for three year running periods. The black regions are the 90% C.L. allowed regions for a combined medium reactor plus long-baseline analysis. The dashed lines indicate a combined analysis with a small reactor measurement.

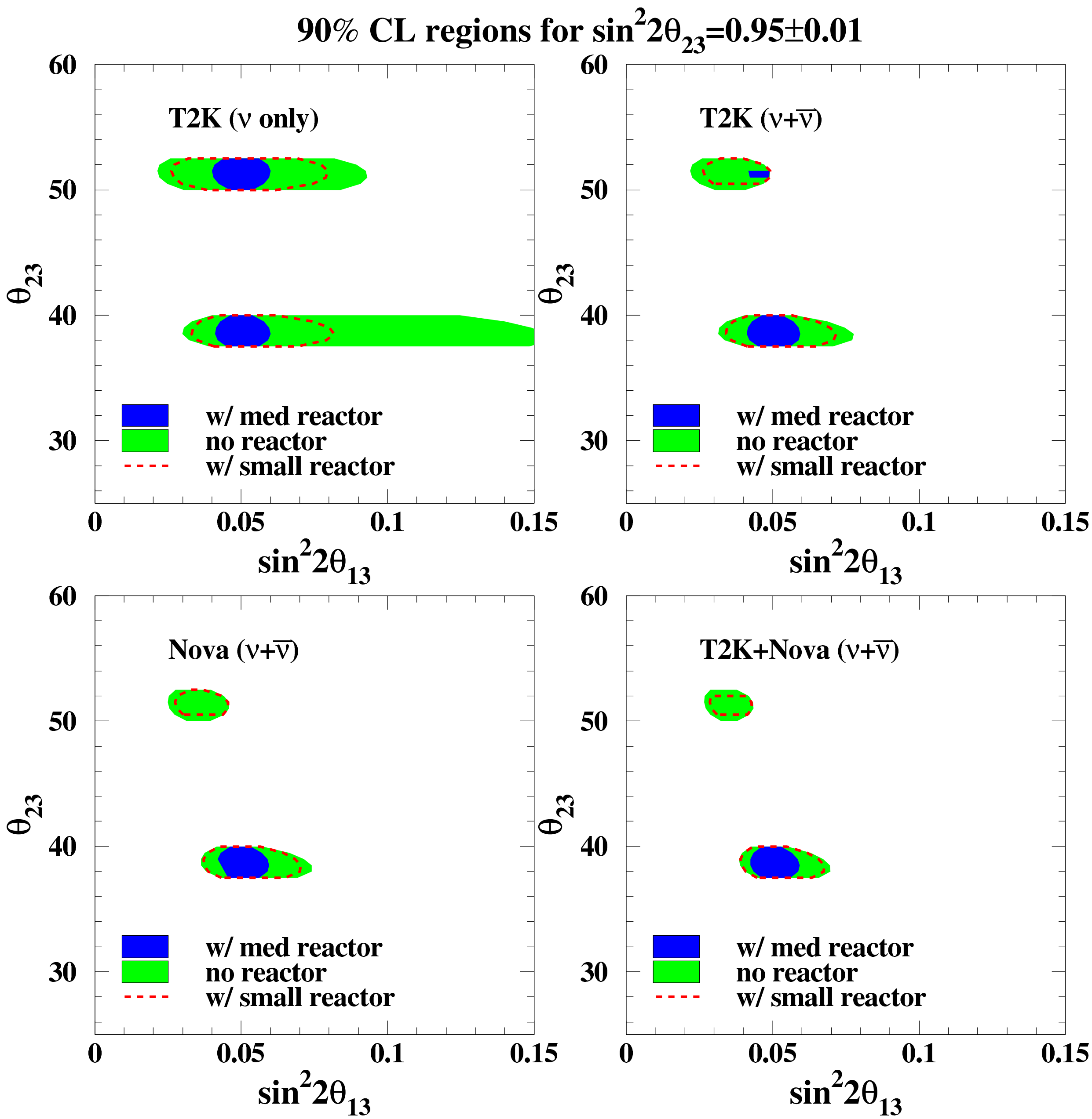

FIG. 4: 90% C.L. allowed regions for simulated data with an underlying oscillation parameters of $\sin^2 2\theta_{13} = 0.05$, $\theta_{23} = 38.54°$, $\Delta m^2 = 2.5 \pm 0.1 \times 10^{-3}$ eV^2 and $\delta_{CP} = 270°$. The analysis includes the restriction that $\sin^2 2\theta_{23} = 0.95 \pm 0.01$. The grey regions are for various long-baseline combinations of the T2K and Nova experiments for three year running periods. The black regions are the 90% C.L. allowed regions for a combined medium reactor plus long-baseline analysis. The dashed lines indicate a combined analysis with a small reactor measurement.

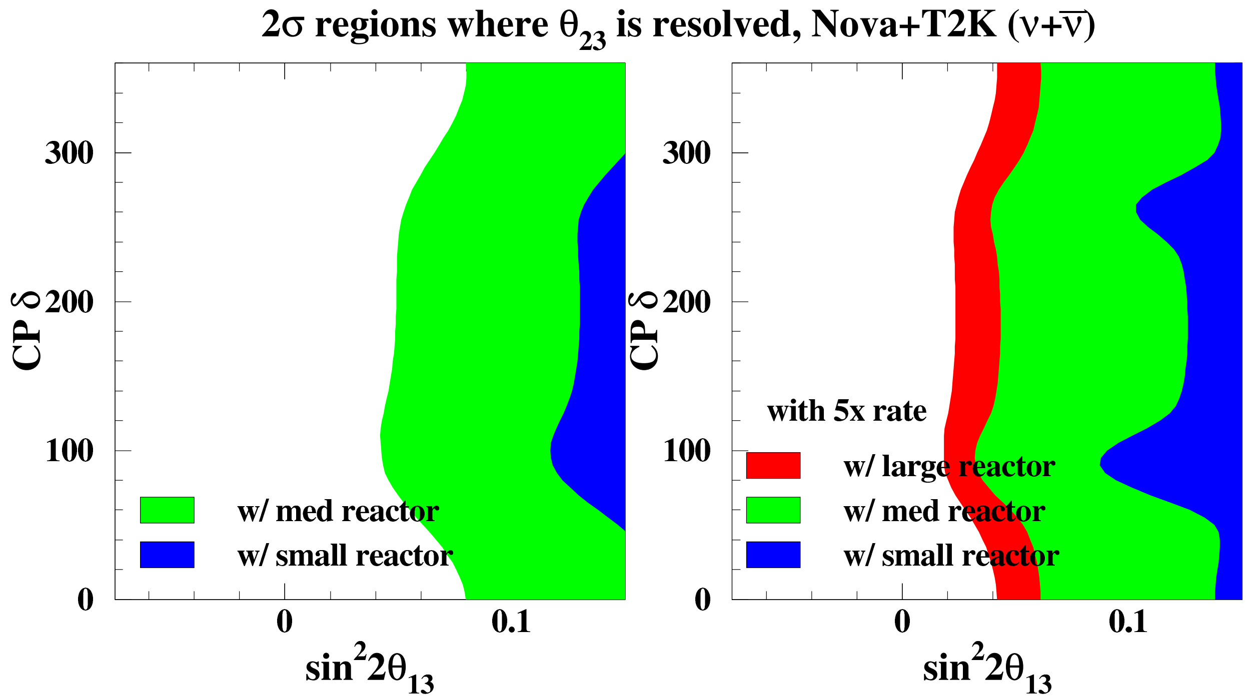

FIG. 5: Regions in the $\delta_{CP} - \sin^2 2\theta_{13}$ plane for which the ambiguity for $\theta_{23} > 45°$ or $< 45°$ is resolved at the two standard deviation level for $\sin^2 2\theta_{23} = 0.95 \pm 0.01$. (The allowed regions are to the right of the curves.) The left plot is the result for a combined data set using the nominal rate T2K and Nova data with medium (light grey) or small (black) scale reactor data. The right plot shows similar results for the enhanced rate ($\times 5$) T2K and Nova data combined with a small (black), medium (light grey), and large (grey) scale reactor data.

IV. CONSTRAINING THE CP VIOLATION PARAMETERS AT 90% C.L. OR DISCOVERY AT 2σ OR 3σ

One of the important goals of an oscillation physics program is to determine if CP violating effects are present in the lepton sector, as probed through the neutrino mixing matrix. In contrast to the reactor disappearance probability, the oscillation probabilities for the long-baseline experiments are affected by the value of the CP violation phase δ_{CP}. Due to these differences, combinations of long-baseline neutrino, antineutrino, and reactor measurements can be used to isolate these CP violating effects and place constraints on δ_{CP} (see Ref. [18]). The size of these effects is scaled by the value of $\sin^2 2\theta_{13}$ which is therefore an important parameter for setting the sensitivity to CP violation. The analysis also needs to include the

uncertainties associated with the other parameters, especially the mass hierarchy.

Figure 6 gives the $\nu_\mu \to \nu_e$ appearance oscillation probability as a function of δ_{CP} for the various combinations of beam type and mass hierarchy for $\sin^2 2\theta_{13} = 0.05$. As seen from the figure, there is a dramatic difference between the T2K and Nova experiments due to matter effects. The goal of a combined oscillation analysis would be to use these differences in the oscillation probabilities to constrain the CP violation phase and the mass hierarchy. For these analyses, reactor measurements provide an unambiguous constraint on the value of $\sin^2 2\theta_{13}$.

From Figure 6, it can also be seen that a measurement of the appearance probability for neutrino running alone could give information on δ_{CP} if the value of $\sin^2 2\theta_{13}$ was known with sufficient accuracy from a reactor oscillation measurement. For high values of $\sin^2 2\theta_{13}$ near the current limit, Figure 7 shows how δ_{CP} can be constrained with neutrino only running for Nova, T2K, and the combination of the two with and without a medium reactor. For the true value of $\delta_{CP} = 90°$, T2K and the reactor narrows down the allowed range in δ_{CP}.

Figure 8 shows how the combinations of various measurements, including antineutrino measurements, can be used to constrain the allowed CP violation phase. The results are for a scenario with $\sin^2 2\theta_{13} = 0.05$ and the optimum phase point $\delta_{CP} = 270°$ (where the difference between the neutrino and antineutrino oscillation probability is the largest for the normal hierarchy). In the upper left plot, a T2K ν–only (3 years) measurement is displayed first without any reactor measurement (grey region), then combined with a medium scale reactor measurement (black region). The upper right plot then shows what happens when both neutrinos (3 years) and antineutrinos (3 years) are used with and without the reactor measurement. Finally, the lower left plot shows the combination of T2K and Nova with and without the reactor result. The medium reactor measurement, in all cases, significantly reduces the uncertainty on θ_{13}.

As a measure of how well the CP phase can be constrained in general, Figure 9 gives the discovery regions in the $\delta_{CP} - \sin^2 2\theta_{13}$ plane for which a null CP violation solution ($\delta_{CP} = 0$ or π) is ruled out by at least three standard deviations. The black regions use long-baseline data only and the grey regions include data from a medium scale reactor experiment. Plot a) is for Nova only, b) is for T2K only and c) includes data from both T2K and Nova. (The results for nominal beam rates are not shown since they do not provide any restrictions at the three standard deviation level.) From the plots, it is seen that the combination of

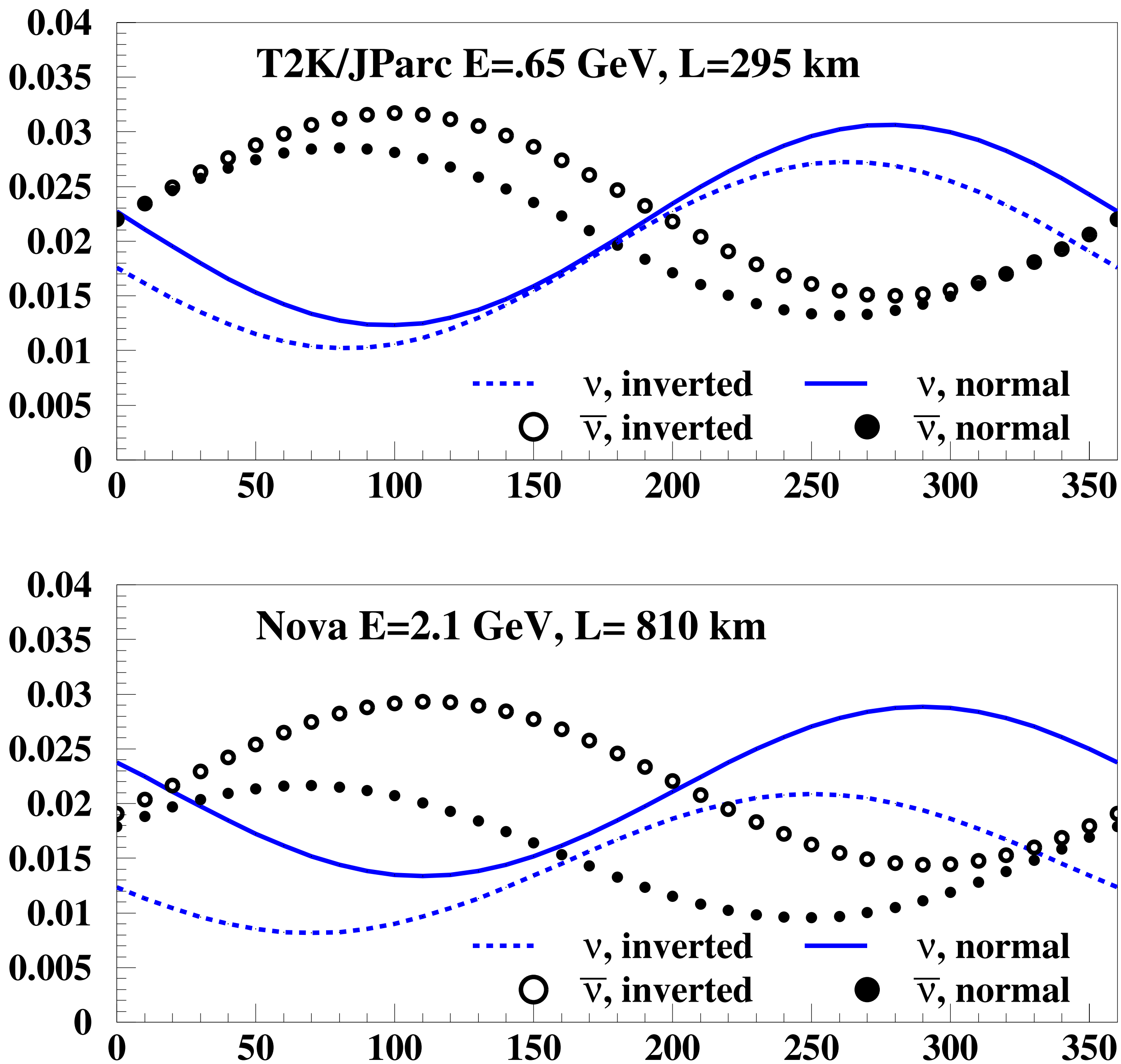

FIG. 6: Oscillation probability for $\nu_\mu \to \nu_e$ appearance vs. δ_{CP} for the T2K (top) and Nova (bottom) experimental setups with $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} = 0.05$ and $\sin^2 2\theta_{23} = 0.95$. The four curves correspond to pure neutrino (solid: normal hierarchy, dashed: inverted hierarchy) or antineutrino (black circle: normal hierarchy, white circle: inverted hierarchy) beams.

T2K and Nova with increased intensity can start to probe the CP violation phase space if $\sin^2 2\theta_{13} \gtrsim 0.02$. (The narrow region in the lower range of δ is due to the ambiguity between normal and inverted hierarchies.) The reactor measurements show how viable a CP violation measurement will be with the various combinations of the long-baseline setups.

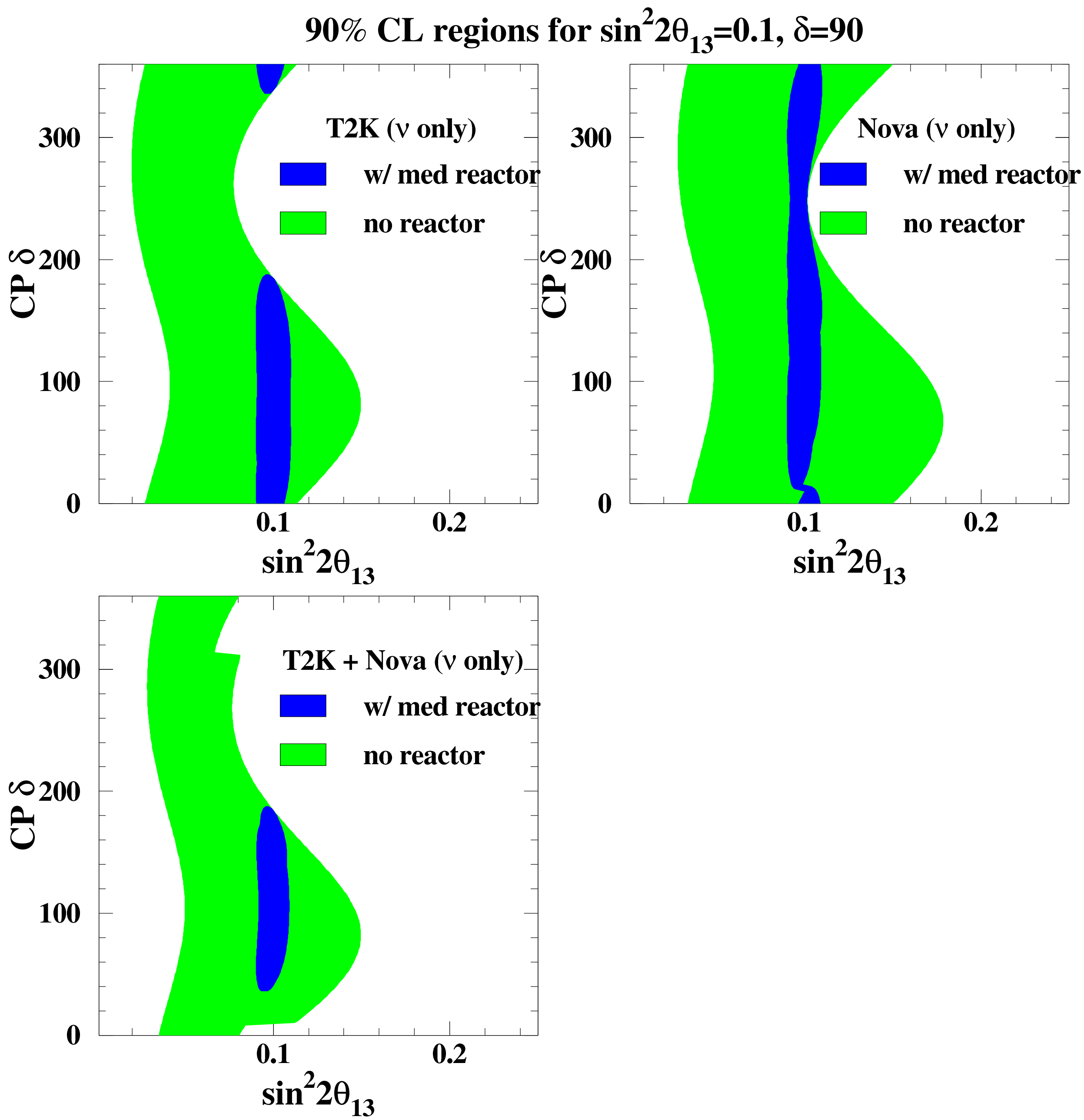

FIG. 7: 90% C.L. regions for underlying oscillation parameters of $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 0.95 \pm 0.01$, $\Delta m^2 = 2.5 \pm 0.1 \times 10^{-3}$ eV^2 and $\delta_{CP} = 90°$. The grey regions are for the T2K, Nova or Nova+T2K experiments for five years of neutrino running. The black regions are the 90% C.L. allowed regions for a combined medium reactor plus long-baseline analysis. The shelf-like discontinuity around $\delta_{CP} = 0°$ and 360° are due to the ability to distinguish the mass hierarchy at those values of δ.

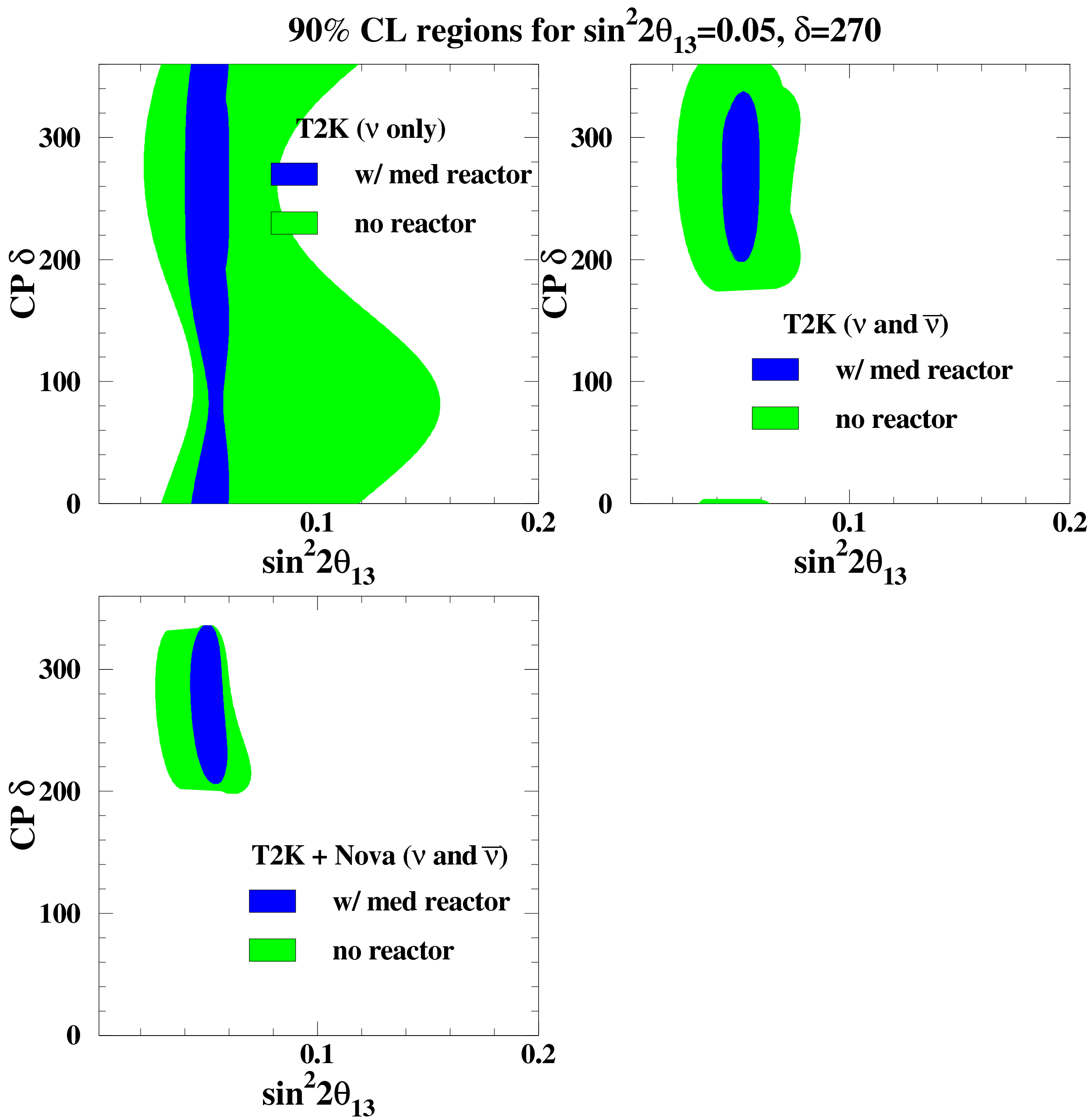

FIG. 8: 90% C.L. regions for various combinations of oscillation results for $\sin^2 2\theta_{13} = 0.05$ and $\delta_{CP} = 270°$ ($\Delta m^2 = 2.5 \pm 0.1 \times 10^{-3}$ eV^2, and $\sin^2 2\theta_{23} = 0.95 \pm 0.01$). Upper Left: 3 year ν–only T2K data with (black) and without (grey) medium scale reactor results. Upper Right: T2K $\nu + \overline{\nu}$ with (black) and without (grey) reactor result. Lower Left: T2K $\nu + \overline{\nu}$ plus Nova $\nu + \overline{\nu}$ with (black) and without (grey) reactor result.

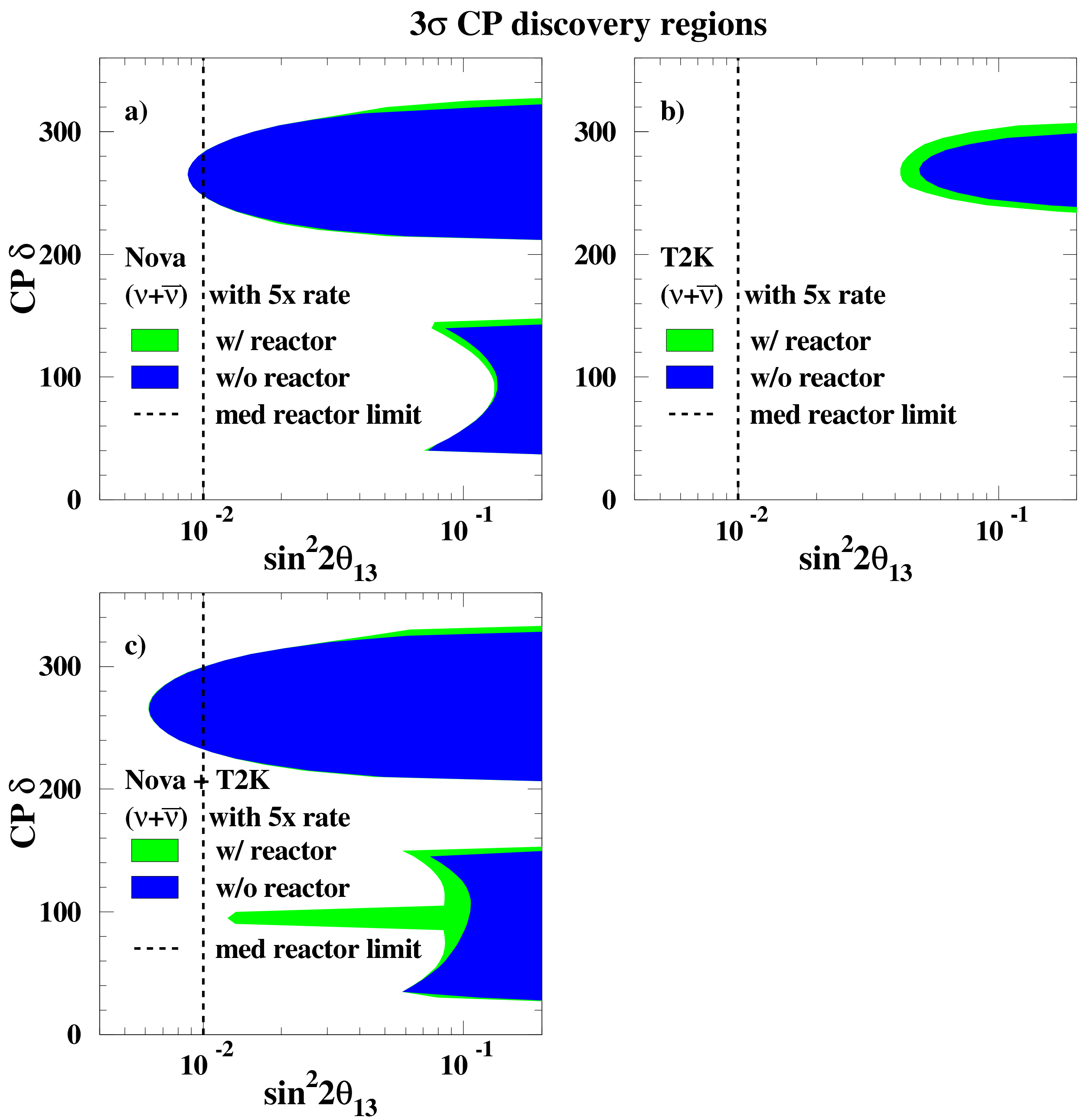

FIG. 9: Discovery regions in the $\delta_{CP} - \sin^2 2\theta_{13}$ plane for which a null CP (δ_{CP}=0,π) violation solution is ruled out by at least three standard deviations. The black regions use long-baseline data only and the grey regions include data from a medium scale reactor experiment. a) Nova ($\times 5$ rate with Proton Driver) ν(3yr) + $\overline{\nu}$(3yr) data; b) T2K ($\times 5$ rate) ν(3yr) + $\overline{\nu}$(3yr) ; c) T2K ($\times 5$ rate) ν(3yr) + $\overline{\nu}$(3yr) + Nova ($\times 5$ rate) ν(3yr) + $\overline{\nu}$(3yr) data. (Nova, T2K and Nova plus T2K with nominal rates is not shown since those combinations are not capable of making a CP violation discovery at the three standard deviation level.) The vertical dashed line indicates the 90% CL upper limit for a medium reactor experiment alone.

V. DETERMINING THE MASS HIERARCHY

For constraining the mass hierarchy, one needs to compare measurements in a region where the oscillation probability changes significantly for a normal versus inverted mass spectrum (see Figure 6). These type of changes can be induced by matter effects as the neutrinos or antineutrinos propagate through material. The Nova experiment is particularly important here due to the long distance the neutrinos travel through the matter of the earth.

An accurate determination of the hierarchy is possible by combining the results from long-baseline neutrino and antineutrino data. Here again, the ambiguity with respect to the value of δ_{CP} limits the determination to regions in the $\sin^2 2\theta_{13} - \delta_{CP}$ plane. Figure 10 shows the regions for which the mass hierarchy is resolved by two standard deviations. The black regions use long-baseline data only and the grey regions add data from a medium scale reactor experiment.

These plots show that the mass hierarchy can be determined for limited regions with $\sin^2 2\theta_{13} > 0.05$ at the nominal beam rates. With the enhanced ($\times 5$) rates, the combination of T2K plus Nova covers most of the δ_{CP} range for $\sin^2 2\theta_{13} > 0.03$. Note that in the upper right plot the black and grey regions lie on top of each other, that is, a reactor doesn't contribute for a short joint run of Nova and T2K but does for a longer one.

VI. OTHER STUDIES

It may be possible in the future to use a very large detector at a site with multiple reactors to push the $\sin^2 2\theta_{13}$ sensitivity down even beyond the "large reactor" scenario to the level of 0.003 at 90% C.L. Combining such a reactor measurement with enhanced long-baseline results improves coverage minimally for a CP measurement and hierarchy determination as compared to a medium reactor, as seen in Figure 11.

Figures 12 and 13 show $\sin\delta_{CP}$ vs $\sin^2 2\theta_{13}$ for future T2K and Nova upgrades. For this study, we consider a Hyper-K upgrade data sample to be equivalent to 150 years ($\times 20$ fiducial mass for 15 years) of T2K running and a Nova Phase II with a proton driver to be equivalent to 50 years ($\times 5$ increased beam rate or detector volume for 10 years) of normal Nova running. These plots, inspired by an earlier paper of Mena and Parke's [15], show clearly the regions of degeneracy.

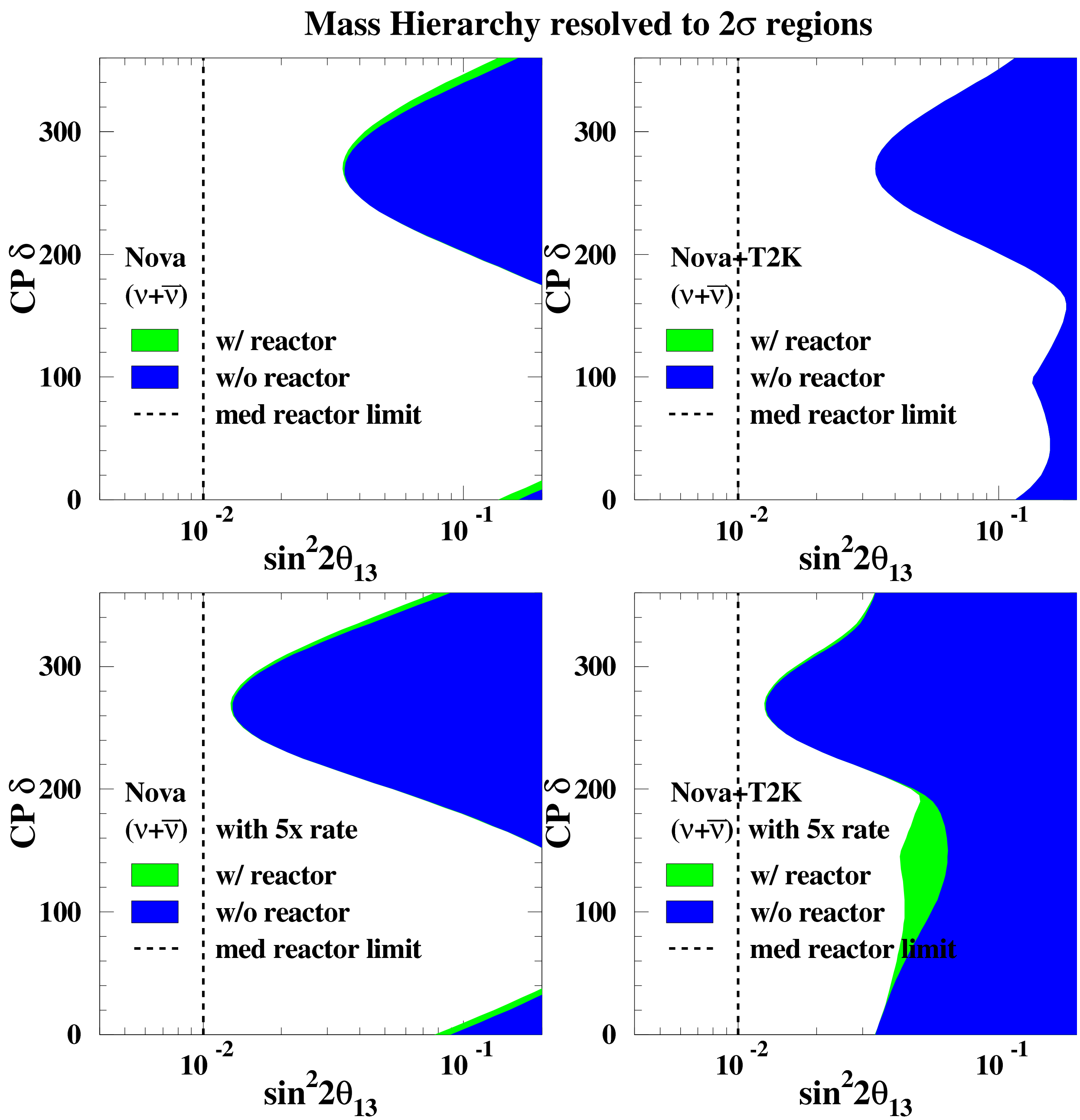

FIG. 10: Regions in the $\delta_{CP} - \sin^2 2\theta_{13}$ plane for which the mass hierarchy is resolved by two standard deviations. The grey regions use long-baseline data only and the black regions add data from a medium scale reactor experiment. a) Nova ν(3yr) + $\overline{\nu}$(3yr) data; b) Nova plus T2K with ν(3yr) + $\overline{\nu}$(3yr) data; c) Nova ($\times$5 beam rate) with ν(3yr) + $\overline{\nu}$(3yr) data; d) T2K ($\times$5 beam rate) ν(3yr) + $\overline{\nu}$(3yr) + Nova ($\times$5 beam rate) ν(3yr) + $\overline{\nu}$(3yr) data. The vertical dashed line indicates the 90% CL upper limit for a medium reactor experiment alone.

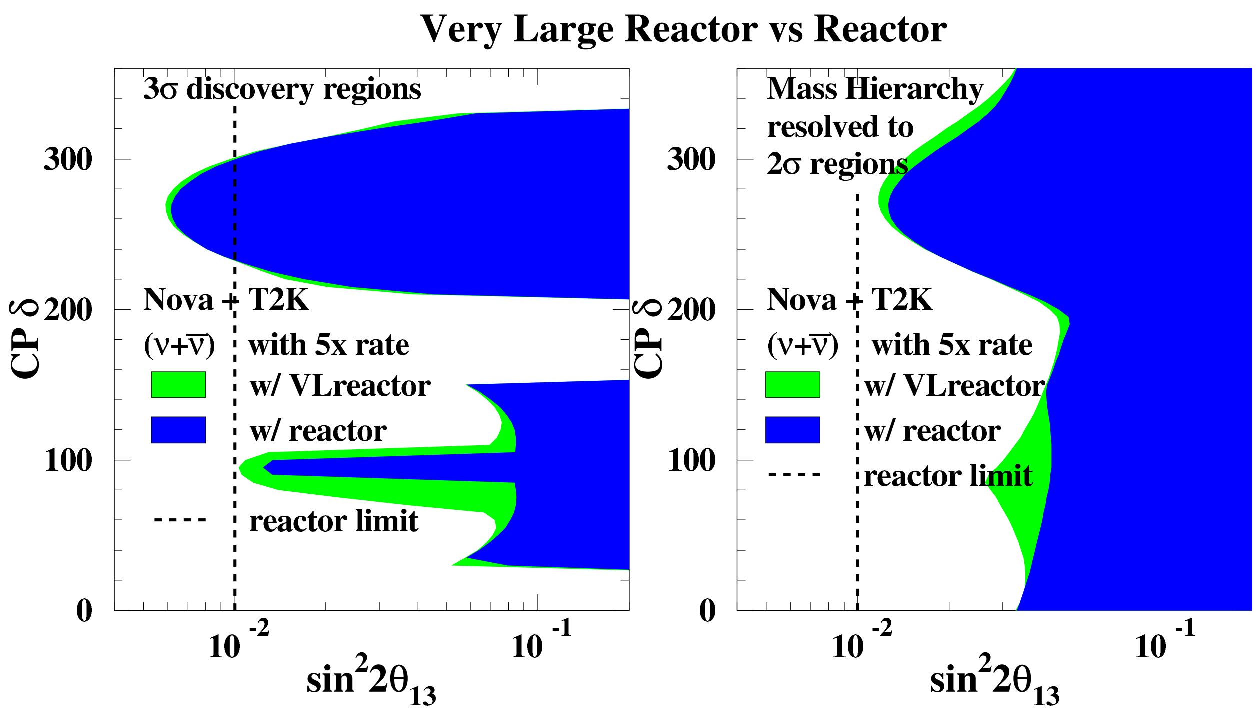

FIG. 11: Regions in the $\delta_{CP} - \sin^2 2\theta_{13}$ plane where null CP violation is ruled out by three standard deviations (left plot) and where the mass hierarchy is resolved by two standard deviations (right plot) for a very large (VL) reactor, with sensitivity of $\sin^2 2\theta_{13} > 0.003$ at 90% C.L. Both plots are for Nova and T2K ($\times 5$ beam rate) with ν(3yr) + $\overline{\nu}$(3yr) data. The black region indicates a measurement including the medium sized reactor, and the grey region includes the very large reactor. The vertical dashed line indicates the 90% CL upper limit for a medium reactor experiment alone.

Ambiguities associated with the mass hierarchy produce multiple solutions and ambiguities associated with θ_{23} give extended regions along the θ_{13} direction. If $\theta_{23} = 45$ degrees, the combination of T2K and Nova correctly determines the mass hierarchy, as shown in Figure 12, and gives only one allowed parameter region. On the other hand, with θ_{23} non maximal ($\theta_{23} = 38.54°$), Figure 13 shows two allowed regions due to the θ_{23} ambiguity that can only be resolved with the addition of a reactor measurement.

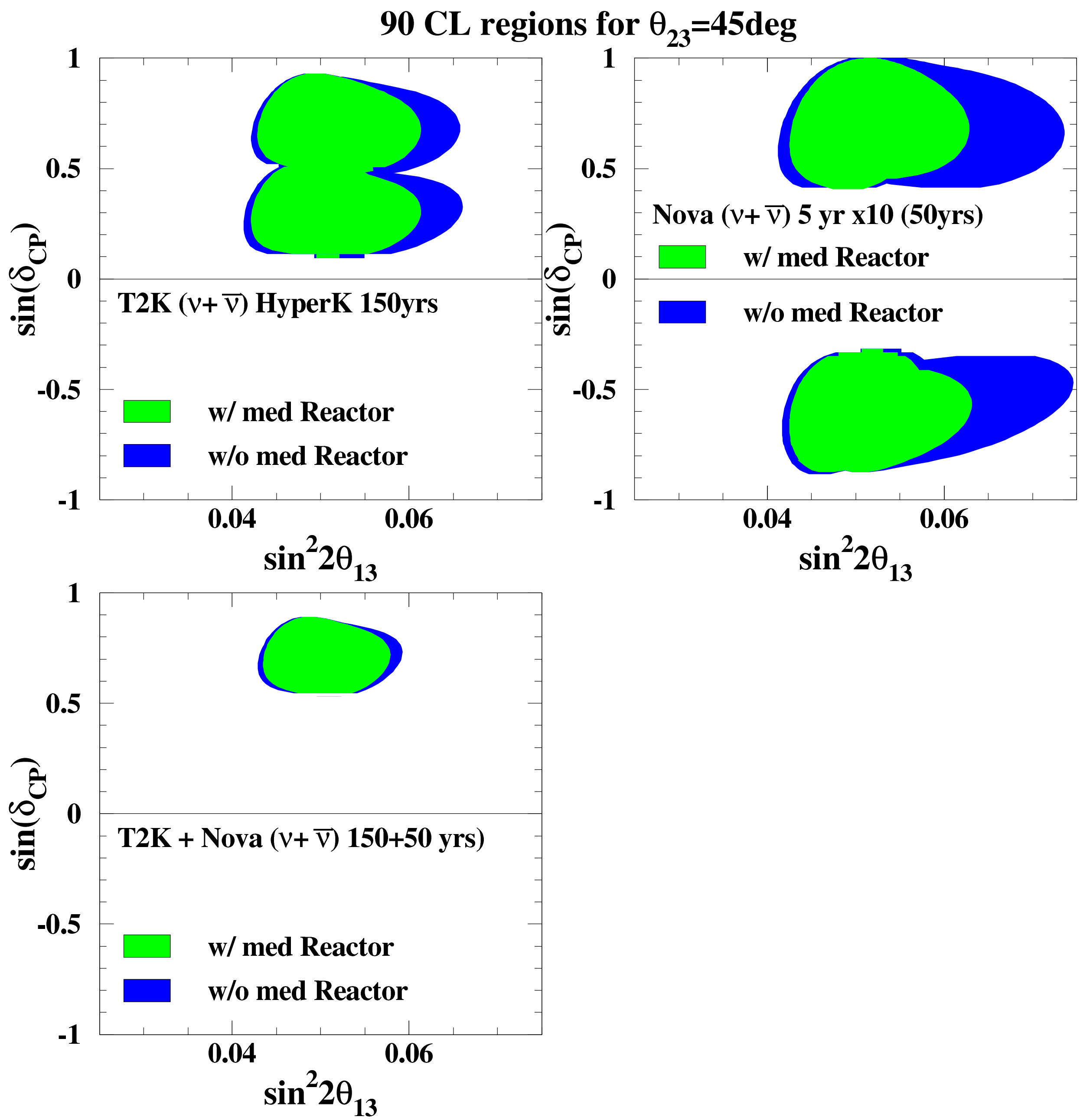

FIG. 12: 90% C.L. allowed regions in the $\sin\delta_{CP} - \sin^2 2\theta_{13}$ plane for T2K (upper left) and Nova (upper right) and T2K (150yrs) and Nova (50yrs) (lower left) shown with the reactor measurement (in grey) and without (in black) all for equal ν and $\overline{\nu}$ running. θ_{23} and Δm^2 are allowed to vary within future uncertainties. $\theta_{23} = 45°$. T2K and Nova combined (lower left plot) correctly resolves the mass hierarchy.

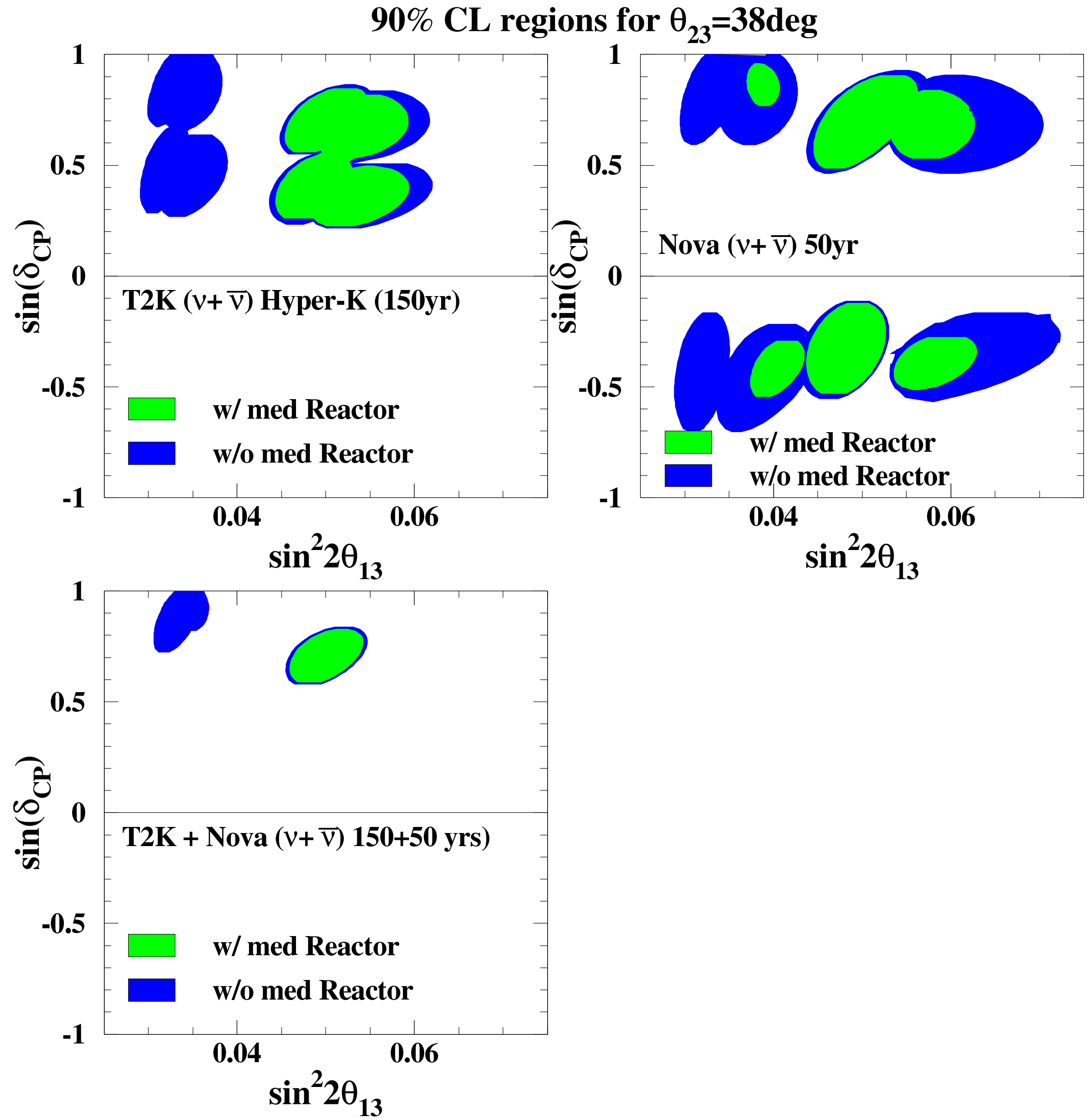

FIG. 13: 90% CL allowed regions in the $\sin\delta_{CP} - \sin^2 2\theta_{13}$ plane for T2K (upper left) and Nova (upper right) and T2K (150yrs) and Nova (50yrs) (lower left) shown with the reactor measurement (in grey) and without (in black) all for equal ν and $\overline{\nu}$ running. θ_{23} and Δm^2 are allowed to vary within future uncertainties. $\theta_{23} = 38.54°$. T2K and Nova combined (lower left plot) correctly resolves the the mass hierarchy only with the additon of a reactor experiment.

VII. CONCLUSIONS

Over the next decade, many experiments are planned to address neutrino oscillations and make improved measurements of the relevant parameters of neutrino mixing. As in the past, combining the results from different types of experiments with different setups will be necessary to map out the underlying physics. In the studies described here, we have tried to investigate the sensitivity using the suite of currently planned or proposed experiments. The complementarity of a program with several long-baseline accelerator experiments and several reactor measurements is clear and, if parameters are favorable, will lead to significant progress in the understanding of neutrino mixing and masses.

As part of this program, reactor measurements hold the promise of constraining or measuring the θ_{13} mixing parameter and helping to resolve the ambiguity in determining the θ_{23} mixing parameter. The sizes of these parameters are important inputs for models of lepton mass and mixing that span the range from GUTs trying to relate the CKM and MNS matrix to extra dimension models that have neutrinos propagating in the bulk. The smallness of θ_{13} relative to the other angles may give a hint as to what the underlying theory may be. Besides leading to a better understanding of neutrino mixing, these angles, θ_{13} and θ_{23}, are two of the twenty-six parameters of the standard model and, as such, are worthy of high precision measurement independently of other considerations. For θ_{13}, a two detector reactor experiment unambiguously measures the size of this angle with significantly better precision than any other proposed experimental technique. In addition, reactor data may be key for resolving the θ_{23} degeneracy.

Looking towards probing CP violation and the mass hierarchy in the neutrino sector, the field will need several high-rate, long-baseline experiments. Here, the size of θ_{13} will be important for interpreting the results and for planning a viable future neutrino oscillation program. In addition to setting the scale for future studies, a reactor result when combined with long-baseline measurements may also give early constraints on CP violation and early indications of the mass hierarchy. In the longer term, a combination of long-baseline experiments such as T2K and Nova will start to give some information about these effects if $\sin^2 2\theta_{13} > 0.05$ and, with some upgrades and enhanced beam rates, will give good coverage if $\sin^2 2\theta_{13} > 0.03$. If θ_{13} turns out to be smaller than these values, one will need other strategies for getting to the physics. Thus, an unambiguous determination θ_{13} from, for

example, a medium scale reactor experiment, is an important ingredient in planning the strategy for this program, as well as accessing the phenomenology of neutrino mixing.

---

[1] P. Huber, M. Lindner, M. Rolinec, T. Schwetz and W. Winter, "Prospects of accelerator and reactor neutrino oscillation experiments for the coming ten years," Phys. Rev. D **70**, 073014 (2004) [arXiv:hep-ph/0403068].

[2] V. D. Barger, S. Geer, R. Raja, and K. Whisnant, Phys. Rev. **D63**, 113011 (2001), [arXiv:hep-ph/0012017].

[3] The Fortran program for the oscillation probability, which includes all effects in a three neutrino mixing model, was provided by S. Parke (Fermilab), parke@fnal.gov.

[4] H. Minakata, H. Sugiyama, O. Yasuda, K. Inoue, and F. Suekane, Phys. Rev. **D68**, 033017 (2003), [arXiv:hep-ph/0211111].

[5] F. James and M. Roos, Comput. Phys. Commun. **10**, 343 (1975).

[6] F. Ardellier *et al.*, "Letter of intent for Double-CHOOZ: A search for the mixing angle theta(13)," [arXiv:hep-ex/0405032].

[7] E. Abouzaid et al. (Braidwood Collaboration) *Braidwood Project Description*, URL `http://braidwood.uchicago.edu/project_web.ps`. Also see URL `http://braidwood.uchicago.edu/`

[8] Daya Bay Neutrino Experiment, URL `http://bes.ihep.ac.cn/dayawane/`.

[9] Y. Ashie *et al.* [Super-Kamiokande Collaboration], "Evidence for an oscillatory signature in atmospheric neutrino oscillation," Phys. Rev. Lett. **93**, 101801 (2004) [arXiv:hep-ex/0404034].

[10] *T2K Letter of Intent* (January 2003), URL `http://neutrino.kek.jp/jhfnu`.

[11] T. Araki *et al.* [KamLAND Collaboration], "Measurement of neutrino oscillation with KamLAND: Evidence of spectral distortion," Phys. Rev. Lett. **94**, 081801 (2005) [arXiv:hep-ex/0406035].

[12] I. Ambats et al. (NOvA) (2004), FERMILAB-PROPOSAL-0929, URL `http://www-off-axis.fnal.gov/`.

[13] *Revised Nova Proposal, March 21, 2005 version*, URL `http://www-nova.fnal.gov/NOvA_Proposal/Revised_NOvA_Proposal.html`.

[14] T. Nakaya, "CP violation in JHF(nu) (Phase II)," *Prepared for 4th Workshop on Neutrino*

Oscillations and their Origin (NOON2003), Kanazawa, Japan, 10-14 Feb 2003 (World Scientific Publishing, 2004 ed. Suzuki, Y, Nakahata, M., Itow, Y., Shiozawa, M., and Obayashi, Y.; ISBN 9812384294)

[15] O. Mena and S. J. Parke, Phys. Rev. D **70**, 093011 (2004) [arXiv:hep-ph/0408070].

[16] H. Minakata, H. Sugiyama, O. Yasuda, K. Inoue, and F. Suekane, Phys. Rev. **D68**, 033017 (2003), [arXiv:hep-ph/0211111].

[17] H. Minakata, M. Sonoyama and H. Sugiyama, "Determination of theta(23) in long-baseline neutrino oscillation experiments with three-flavor mixing effects," Phys. Rev. D **70**, 113012 (2004) [arXiv:hep-ph/0406073].

[18] H. Minakata and H. Sugiyama, Phys. Lett. **B580**, 216 (2004), [arXiv:hep-ph/0309323].